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14. ABSTRACT
Design of cockpit pressurization systems impacts operational exploitation of the maximal altitude capabilities of some aircraft. The U-2 exposes the pilot to a cockpit altitude of approximately 30,000 ft with a 3.8 psid pressurization system. Approximately 70% of active/retired U-2 pilots reported that decompression sickness (DCS) occurred during their career of flying 9-hour missions at this altitude. Design of the F-22 pressurization system was based on previous fighter aircraft systems which maintain 5.0 psi differential pressure above 23,000 ft. Unfortunately, the 60,000 ft planned cruise capability of the F-22 places the pilot at 22,500 ft. The recently-reported threshold for DCS while breathing 100% oxygen is approximately 21,000 ft. The threshold altitude, which is lower than USAF and FAA regulations currently allow for unpressurized flight, implies a need for greater cockpit differential pressure for the F-22 and reinforces the need for breathing 100% oxygen prior to and including the high altitude portions of the flight profile. Increasing the cockpit differential pressure to keep the pilot at less than 21,000 ft would eliminate the vast majority of DCS cases. Breathing 100% oxygen during this period would provide additional protection from hypoxia in the event of unexpected rapid decompression. Another recent finding indicates that denitrogenation by breathing 100% oxygen at altitudes up to 16,000 ft is as effective as ground-level prebreathing. In addition, gas emboli formation at 16,000 ft is lower than at higher altitudes. Continuing research in altitude physiology would help define optimal design parameters.

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IMPACT OF RECENT ALTITUDE PHYSIOLOGY RESEARCH ON DESIGN OF COCKPIT PRESSURIZATION SYSTEMS

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ABSTRACT
Design of cockpit pressurization systems impacts operational exploitation of the maximal altitude capabilities of some aircraft. The U-2 exposes the pilot to a cockpit altitude of approximately 30,000 ft with a 3.8 psid pressurization system. Approximately 70% of active/retired U-2 pilots reported that decompression sickness (DCS) occurred during their career of flying 9-hour missions at this altitude. Design of the F-22 pressurization system was based on previous fighter aircraft systems which maintain 5.0 psi differential pressure above 23,000 ft. Unfortunately, the 60,000 ft planned cruise capability of the F-22 places the pilot at 22,500 ft. The recently-reported threshold for DCS while breathing 100% oxygen is approximately 21,000 ft. The threshold altitude, which is lower than USAF and FAA regulations currently allow for unpressurized flight, implies a need for greater cockpit differential pressure for the F-22 and reinforces the need for breathing 100% oxygen prior to and including the high altitude portions of the flight profile. Increasing the cockpit differential pressure to keep the pilot at less than 21,000 ft would eliminate the vast majority of DCS cases. Breathing 100% oxygen during this period would provide additional protection from hypoxia in the event of unexpected rapid decompression. Another recent finding indicates that denitrogenation by breathing 100% oxygen at altitudes up to 16,000 ft is as effective as ground-level prebreathing. In addition, gas emboli formation at 16,000 ft is lower than at higher altitudes. Continuing research in altitude physiology would help define optimal design parameters.

BACKGROUND

Prevention of Hypoxia with Supplemental Oxygen

Physiologic incidents associated with flight at high altitude; i.e., 30,000-45,000 ft, became rare following the advent of pressurized cabins and better oxygen equipment during and after WWII. However, as pointed out by Ernsting[6], compromises have been made in establishing an adequate environment and breathing mixture for a crewmember flying at high altitude. Dr. Ernsting discussed prevention of serious hypoxia following rapid decompression to altitudes exceeding 30,000 ft and the need for oxygen concentrations in excess of 40% prior to such decompression. In a workshop on the life support and physiological issues of flight at 60,000 feet and above[10], he[5] pointed out two important disadvantages associated with use of a breathing mixture containing a high concentration of oxygen during flight in agile combat aircraft. Utilization of oxygen by tissues can remove oxygen from the gaseous state, leading to: 1) collapse of alveoli under acceleration forces and 2) delayed

otitic barotrauma. A compromise was required between the need for higher concentrations of oxygen prior to rapid decompression[6] and inclusion of nitrogen in the breathing mixture for prevention of acceleration atelectasis[2] and delayed otitic barotrauma. The upper limit for oxygen concentration was agreed to be 60% at 15,000 ft and 75% at 20,000 ft[2]. This level of oxygen is sufficient to prevent severe hypoxia in the event of rapid decompression to 30,000 ft and provides enough nitrogen to prevent acceleration atelectasis. However, during altitude chamber decompressions, nitrogen in the breathing mixture has been shown to increase the level of venous gas emboli (VGE)[16] and DCS[3] relative to the level observed in subjects breathing 100% oxygen.

Prevention of Decompression Sickness with Cabin Pressurization Although use of pressurized cabins greatly reduced the incidence of DCS in WWII bombers and fighter aircraft, the U-2 has inadequate pressurization at normal cruise altitude. Surveys of active and retired USAF high-altitude U-2 reconnaissance pilots have revealed that, "...during their careers, 75.5% of pilots experienced DCS symptoms such as joint pain, skin manifestations, and/or various neurological problems"[4]. The 3.8 psid pressurization system was inadequate to protect the pilots from DCS, even after prebreathing with 100% oxygen for an hour prior to each mission. The operational exposures to approximately 30,000 ft cabin altitude are accomplished regularly by U-2 pilots, and have been simulated in altitude chambers at the Armstrong Laboratory, Brooks AFB, TX. The results have indicated that 70-85% of the subjects experienced DCS during 4 to 8-hour exposures[15,17] a finding consistent with the concept that these exposures represent a high risk of symptom development. Prevention of DCS in future high altitude reconnaissance aircraft could be achieved by increasing the cockpit differential pressure or using increased suit pressure to provide the pilot with a more physiologically acceptable environment.

The F-22 is planned to have a 60,000-ft cruise altitude capability. With a planned 5-psid cockpit pressurization system, the resulting 22,500-ft cockpit places the pilot at increased risk for developing DCS symptoms[17]. The risk of DCS has previously been considered minimal below 25,000 ft, despite several reported incidents of DCS in aircraft where the crewmember/s were exposed to lower altitudes[7,8,13]. Future aircraft capable of sustained flight above 50,000 ft will require both higher differential cabin pressures and advancements in personal life support equipment to sustain the crewmember during and following rapid decompression. Some recent research provides data which could aid in development of future aircraft pressurization systems and life support equipment.

Recent Research Current USAF (AFI 11-206) and FAA guidelines (FAR Parts 91.211 and 121.327-333) allow crewmembers to be exposed to 25,000 ft without preoxygenation, indeed, without even breathing 100% oxygen. Recent research at the Armstrong Laboratory has shown a 5% risk of DCS at 20,500 ft, without preoxygenation (prebreathing), increasing to 90% at 25,000 ft[17]. These data support development of a 21,000-ft cockpit for those cases where cabin depressurization will not occur or where further depressurization to more than 30,000 ft will only be for a few minutes.

In those cases where a depressurization will not be corrected by descent within 5 min, a 16,000-ft cockpit better protects a crewmember from the potential for rapid growth of gas emboli formed prior to the decompression. With no prebreathe, but using 100% oxygen during exposure, gas emboli formation is lower at 16,000 ft than at higher altitudes (Fig. 1[16,17]). The Pilmanis et al. paper[9] reports equivalent effectiveness of prebreathe from ground level up to 16,000 ft, with some DCS and higher levels of gas emboli at 18,000 ft. The ground-level prebreathe and prebreathe at altitude was followed by exposure to 30,000 ft, during which higher levels of DCS occurred if the prebreathe occurred at 18,000 ft rather than at lower altitudes.

Gas emboli formation is only important for sustained flight above 43,000 ft in a 5-psid cockpit, because it is in this 18,000-ft+ cockpit environment where gas emboli would form during a half hour of cruise flight

Figure 1. Incidence of Venous Gas Emboli (VGE) and Decompression Sickness (DCS) during Zero-Prebreathe Exposure to Altitude.

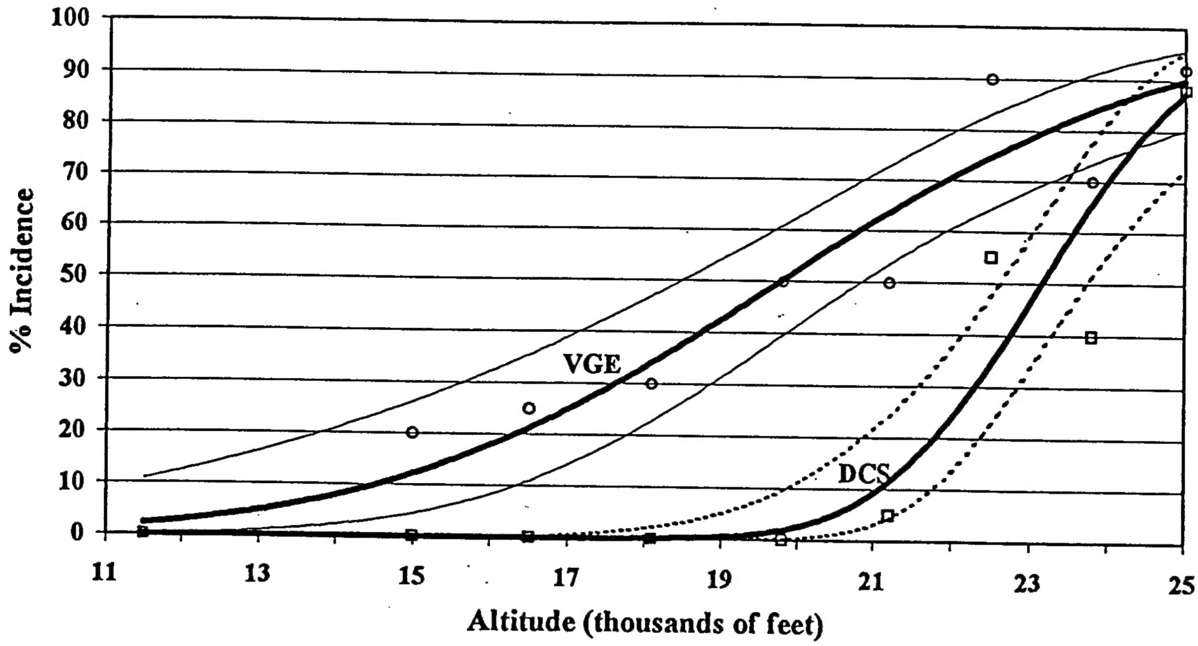
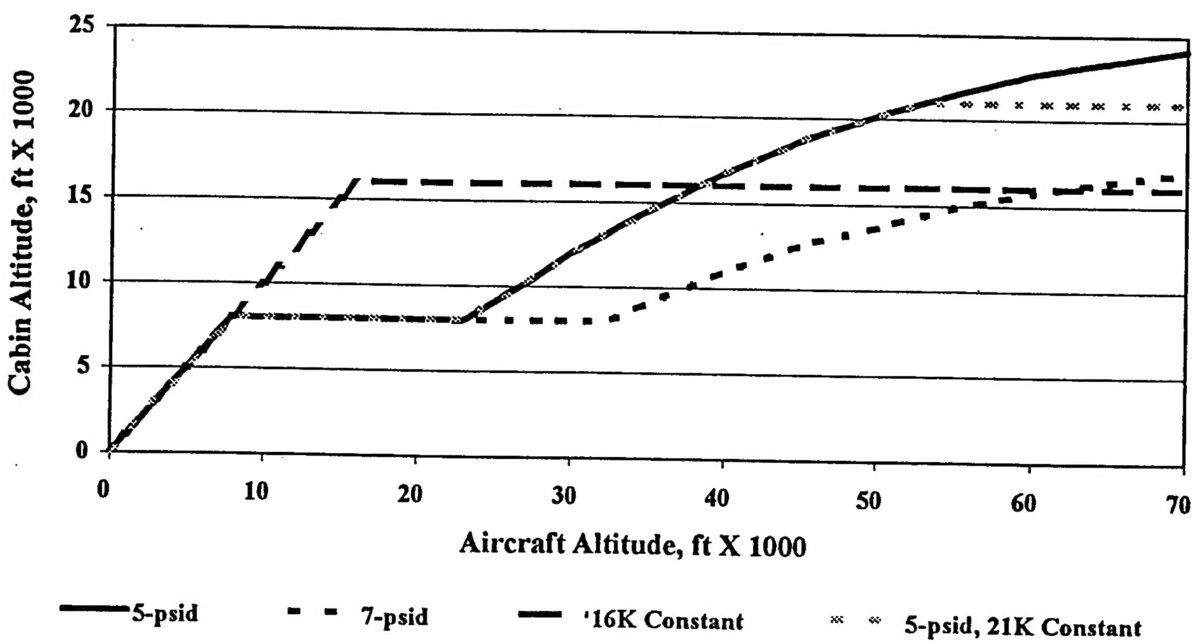


Figure 2. Cockpit Pressurization Schedules



and increase in diameter during a subsequent rapid decompression. It would be necessary to increase the differential pressure above 5 psid beginning at 38,000 ft to keep the pilot at 16,000 ft. At 16,000 ft, the pilot would, in effect, be prebreathing (100% oxygen) with ground-level effectiveness. To keep the pilot at 21,000 ft constant altitude, safe from DCS symptoms without further decompression, pressurization would need to be more than 5 psid above 53,000 ft (Fig. 2). However, if cruise altitudes reach 70,000 ft, the differential pressure necessary to maintain the crew at 16,000 ft becomes 7.3 psid. To maintain a 21,000-ft cockpit altitude during cruise at 70,000 ft requires 5.8 psid. A differential pressure of 7 psid approaches the tolerance limit for unprotected human lungs and must be accompanied by adequate, nearly full-body, counter-pressure if the aircraft must remain at high altitude for more than a minute after decompression. The United Kindgom's Tornado aircraft uses a pressurization schedule which allows a decreased rate of decompression from 5,000 ft to 38,000 ft, followed by a constant 5.25 psid with atmospheric pressure[5].

RECOMMENDATIONS

Based on recent research results and projected capabilities of future fighter aircraft, additional altitude protection will become necessary. Anticipation of the potential for decompression to an aircraft cruise altitude of 70,000 ft drives design of pilot protective equipment to provide a minimum of 141 mm Hg (absolute pressure; i.e., atmospheric pressure plus oxygen pressure supplied by the regulator) of 100% oxygen to the pilot's oxygen mask regardless of altitude. This level of pressure is equivalent to the atmospheric pressure at 40,000 ft. When breathing 100% oxygen at 141 mm Hg, the pilot is at a physiologic equivalent of 10,000 ft (60 mm Hg alveolar oxygen tension). This pressure of oxygen would ensure adequate, near-peak performance for at least 30-min following rapid decompression, allowing continuation of cruise at high altitude. However, ensuring that 141 mm Hg (absolute pressure) is available to the pilot requires modification of current pilot protective equipment. The get-me-down concepts used currently in fighter aircraft employ positive pressure breathing for altitude, and some provide 32 mm Hg of assisted positive pressure breathing via a counter-pressure jerkin, e.g. COMBAT EDGE at 50,000 ft. This concept fails if the mission dictates continued flight at altitudes above 50,000 ft following rapid decompression. There would be inadequate oxygen to maintain performance. The F-22 life support system only provides short-term get-me-down protection up to 60,000 ft with up to 70 mm Hg of assisted positive pressure breathing. It cannot provide an adequate environment for sustained exposure. The get-me-down concept must evolve into a keep-me-up concept. The keep-me-up concept involves development of a modified, pilot-acceptable, full-pressure head/neck enclosure integrated with a chest counter-pressure jerkin and lower-body pressure assembly described by Self et al. in these symposia proceedings. This concept could provide sustained protection to 70,000 ft and could also provide adequate anti-G protection.

A cockpit pressurization schedule which does not allow the cockpit to exceed 21,000 ft would keep the pilot safe from symptoms of DCS, particularly if the time at 21,000 ft was limited to less than 30 min. However, since unplanned depressurization can occur, and, in the past, has occurred in every pressurized operational fighter, the issue of a higher cockpit pressurization system becomes important. The use of 16,000 ft as a maximum cabin altitude limits incidence of gas emboli in blood and the effects of their increase in diameter during a rapid decompression. The ensemble described by Self et al. (These Symposia Proceedings) would limit effect of the decompression on body tissues protected by an ensemble providing a total pressure of 141 mm Hg (2.72 psia; 40,000 ft) to the vast majority of the body. Therefore, during a decompression of the cockpit from 16,000 ft to 70,000 ft, the body would only be exposed to a 5.25 psi decompression (7.97 psi to 2.72 psia; 16,000 ft to 40,000 ft). The limit of 16,000 ft would delay onset of gas emboli formation to beyond 30 min and ensure minimal to zero DCS assuming 100% oxygen is provided from before takeoff.

Several pressurization scenarios could be used to obtain a constant 21,000-ft or 16,000-ft cabin altitude. The current USAF fighter aircraft

pressurization schedule could be employed until the cabin pressure drops to 16,000 ft (8 psia) or 21,000 ft (6.5 psia). Increasing differential pressures above that altitude are required to maintain 16,000 ft or 21,000 ft. A second option to obtain a 16,000-ft cockpit would be to extend the region of unpressurized flight from ground level to 16,000 ft (vice 8,000 ft), followed by addition of differential pressure to maintain 16,000 ft. A combination of these schedules is also feasible, as long as the pilot's environmental pressure does not exceed the desired maximum altitude unless an unplanned decompression occurs.

CONCLUSION

Incorporation of adequate altitude protection for fighter operations well above 50,000 ft involves both redesign of personal equipment and redesign of the cockpit pressurization system. The consequences of not accomplishing either redesign involves greatly reduced time at high altitude, unconsciousness following an unplanned decompression, and/or increased incidence and severity of DCS, possibly even before an unplanned decompression.

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BIOGRAPHIES

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